CSCE 313-200
Introduction to Computer Systems
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Synchronization V

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Updates

- Memory heaps
  - Normal new/delete ops go to the process heap
  - Internal mutex, slow delete
- Private heap doesn't need to mutex
  - Benchmark with 12 threads on a 6-core system

```
#define ITER   1e7
DWORD __stdcall HeapThread (...) {
    DWORD **arr = new (DWORD *) [ITER];
    for (int i=0; i < ITER; i++)
          arr[i] = new DWORD [1];

    for (int i=0; i < ITER; i++)
          delete arr[i];
}
```

3.3M/s

```
DWORD __stdcall HeapThread (...) {
   HANDLE heap = HeapCreate
          (HEAP_NO_SERIALIZE,
          4 * 1024 * sizeof(DWORD), 0);

   DWORD **arr = new (DWORD *) [ITER];
   for (int i = 0; i < ITER; i++)
          arr[i] = (DWORD*) HeapAlloc
           (heap, HEAP_NO_SERIALIZE,
                    sizeof(DWORD));
   HeapDestroy (heap);
}
```

36M/s

```
DWORD __stdcall HeapThread (...) {
   HANDLE heap = HeapCreate
          (HEAP_NO_SERIALIZE,
          4 * 1024 * sizeof(DWORD), 0);

   DWORD **arr = new (DWORD *) [ITER];
   for (int i=0; i < ITER; i++)
          arr[i] = (DWORD*) HeapAlloc
           (heap, HEAP_NO_SERIALIZE,
                    sizeof(DWORD));

   for (int i=0; i < ITER; i++)
          HeapFree (heap,
              HEAP_NO_SERIALIZE, arr[i]);
}
```

12M/s

Chapter 5: Roadmap

5.1 Concurrency

5.2 Hardware mutex

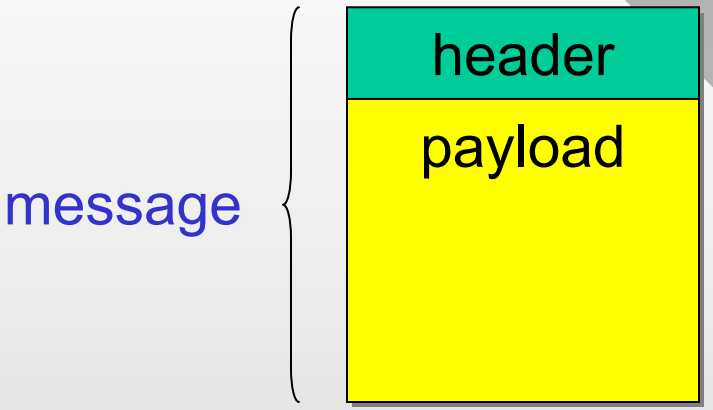
5.3 Semaphores

5.4 Monitors

5.5 Messages

5.6 Reader-Writer

Messages



- Messages are discrete chunks of information exchanged between processes
  - This form of IPC is often used between different hosts
- Where used
  - Pipes (one-to-one)
  - Mailslots (one-to-many among hosts in the active directory domain)
  - Sockets (TCP/IP)
- In general form, message consists of fixed header and some payload
- Header may specify
  - Version and protocol #
  - Message length, type, various attributes
  - Status and error conditions
- Already studied enough in homework #1

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5.6 Reader-Writer

Reader-Writer (RW)

- RW is another famous synchronization problem
- Assume a shared object that is accessed by M readers and K writers in parallel
- Example: suppose hw#1 restricted robot MOVE commands to only adjacent rooms
  - This requires construction of a global graph G as new edges are being discovered from the threads (writer portion)
  - To make a move, each thread has to plot a route to the new location along the shortest path in G (reader portion)
- Any number of readers may read concurrently
  - However, writers need exclusive access to the object (i.e., must mutex against all readers and other writers)

Reader-Writer

- Q: based on your intuition, do readers or writers usually access the object more frequently?
- First stab at the problem:
  - RW 1.0

```
Reader::GoRead () {
    mutexRcount.Lock();
    // first reader blocks writers
    if (readerCount == 0)
        semaW.Wait();
    readerCount ++;
    mutexRcount.Unlock();

    // read object

    mutexRcount.Lock();
    readerCount--;
    // last reader unblocks writers
    if (readerCount == 0)
        semaW.Release();
    mutexRcount.Unlock();
}
```

```
Writer::GoWrite () {
    semaW.Wait();
    // write object
    semaW.Release();
}
```

- Infinite stream of readers?
  - Writers never get access
- RW 1.0 gives readers priority and starves writers

Reader-Writer

increasing writer thread priority
may help against being starved

- Another policy is to let the OS load-balance the order in which readers and writers enter the critical section
  - RW 1.1

```
Reader::GoRead () {
    semaWriterPending.Wait();
    semaWriterPending.Release();
    mutexRcount.Lock();
    // first reader blocks writers
    if (readerCount == 0)
        semaW.Wait();
    readerCount ++;
    mutexRcount.Unlock();

    // read object

    mutexRcount.Lock();
    readerCount--;
    // last reader unblocks writers
    if (readerCount == 0)
        semaW.Release();
    mutexRcount.Unlock();
}
```

```
Writer::GoWrite () {
    semaWriterPending.Wait();
    semaW.Wait();
    // write object
    semaW.Release();
    semaWriterPending.Release();
}
```

- Serves readers/writers in FIFO order if kernel mutex is fair
- What if 100x more readers than writers?

Reader-Writer

- Final policy: writers have absolute priority
  - Given a pending writer, no reader may enter
  - RW 1.2

```
Reader::GoRead () {
    semaWriterPending.Wait();
    semaWriterPending.Release();
    mutexRcount.Lock();
    // first reader blocks writers
    if (readerCount++ == 0)
        semaW.Wait();
    mutexRcount.Unlock();

    // read object

    mutexRcount.Lock();
    // last reader unblocks writers
    if (--readerCount == 0)
        semaW.Release();
    mutexRcount.Unlock();
}
```

OS chooses between one writer and M readers

```
Writer::GoWrite () {
    mutexWcount.Lock();
    if (writerCount++ == 0)
        semaWriterPending.Wait();
    mutexWcount.Unlock();

    semaW.Wait();
    // write object
    semaW.Release();

    mutexWcount.Lock();
    if (--writerCount == 0)
        semaWriterPending.Release();
    mutexWcount.Unlock();
}
```

- Works fine except first writer still must compete

Reader-Writer

- To ensure priority for the first writer, need to prevent readers from competing for semaWriterPending
  - RW 1.3

```
Reader::GoRead () {
    mutexDontCompete.Lock();
    semaWriterPending.Wait();
    mutexRcount.Lock();
    // first reader blocks writers
    if (readerCount++ == 0)
        semaW.Wait();
    mutexRcount.Unlock();
    semaWriterPending.Release();
    // pending writer gets unblocked here
    mutexDontCompete.Unlock();

    // read object

    mutexRcount.Lock();
    // last reader unblocks writers
    if (--readerCount == 0)
        semaW.Release();
    mutexRcount.Unlock();
}
```

```
Writer::GoWrite () {
    mutexWcount.Lock();
    if (writerCount++ == 0)
        semaWriterPending.Wait();
    mutexWcount.Unlock();

    semaW.Wait();
    // write object
    semaW.Release();

    mutexWcount.Lock();
    if (--writerCount == 0)
        semaWriterPending.Release();
    mutexWcount.Unlock();
}
```

- Textbook solution
  - Works even if semaphore is unfair

Reader-Writer

- What about the next solution that eliminates one lock and rearranges some of the lines
  - RW 1.4

```
Reader::GoRead () {
    mutexRcount.Lock();
    semaWriterPending.Wait();
    if (readerCount++ == 0)
        // first reader blocks writers
        semaW.Wait();
    semaWriterPending.Release();
    // pending writer gets unblocked here
    mutexRcount.Unlock();

    // read object

    mutexRcount.Lock();
    // last reader unblocks writers
    if (--readerCount == 0)
        semaW.Release();
    mutexRcount.Unlock();
}
```

```
Writer::GoWrite () {
    mutexWcount.Lock();
    if (writerCount++ == 0)
        semaWriterPending.Wait();
    mutexWcount.Unlock();

    semaW.Wait();
    // write object
    semaW.Release();

    mutexWcount.Lock();
    if (--writerCount == 0)
        semaWriterPending.Release();
    mutexWcount.Unlock();
}
```

- Find a problem at home

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Performance

Windows APIs

- GetCurrentProcess() and GetCurrentProcessId()
  - Return a handle and PID, respectively
- EnumProcesses(), OpenProcess()
  - Enumerates PIDs in the system, opens access to them
- TerminateProcess() kills another process by its handle
  - ExitProcess() voluntarily quits (similar to C-style exit())
- GetProcessTimes()
  - Time spent on the CPU (both in kernel-mode and user-mode)
- Available resources
  - GlobalMemoryStatus(): physical RAM, virtual memory
  - GetActiveProcessorCount(): how many CPUs
- CPU utilization: see cpu.cpp in sample project

Performance

```
CRITICAL_SECTION cs;
InitializeCriticalSection (&cs);
// mutex.Lock()
EnterCriticalSection (&cs);
// mutex.Unlock()
LeaveCriticalSection (&cs);
```

- WaitForSingleObject
  - Always makes a kernel-mode transition and is pretty slow
  - Mutexes, semaphores, events all rely on this API
- A faster mutex is CRITICAL_SECTION (CS)
  - Busy-spins in user mode on interlocked exchange for a fixed number of iterations
  - If unsuccessful, gives up and locks a kernel mutex
- While kernel objects (i.e., mutexes, semaphores, events) can be used between processes, CS works only between threads *within* a process

Performance

```
CONDITION_VARIABLE cv;
InitializeConditionVariable (&cv);
```

- Condition variables in Windows
  - In performance, similar to CS (i.e., spins in user mode)
  - Secret (monitor) mutex is explicit pointer to some CS
- PC 3.0 that actually works in Windows

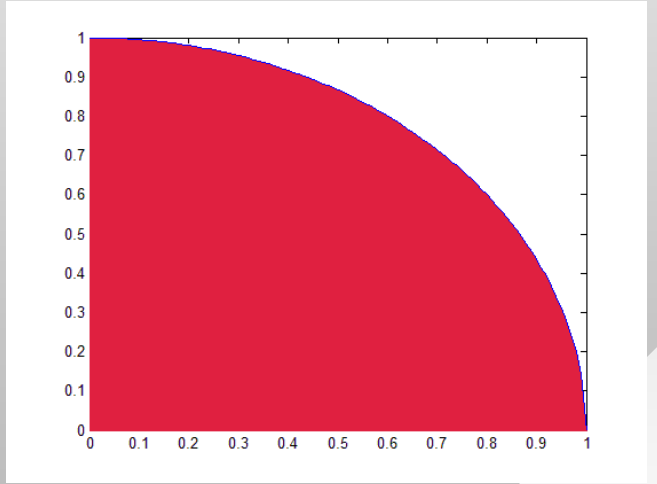
```
pcQueue::push (Item x) {
    EnterCriticalSection (&cs);
    while ( Q.isFull () )
          SleepConditionVariable (&cvNotFull, &cs, ...);
    Q.add (x);
    LeaveCriticalSection (&cs);
    WakeConditionVariable (&cvNotEmpty);
}
```

pop() is similar

- Slim RW locks
  - AcquireSRWLockShared (reader)
  - AcquireSRWLockExclusive (writer)

Performance

- Example 1: compute π in a Monte Carlo simulation
  - Generate N random points in 1x1 square and compute the fraction of them that falls into unit circle at the origin
  - Probability to hit the red circle?
- This probability is the visible area of the circle divided by the area of the square (i.e., 1)
  - Quarter of a circle gives us $\pi/4$




```
DWORD WINAPI ThreadPi (LONG *hitCircle) {
    for (int i=0; i < ITER; i++) {
          // uniform in [0,1]
          x = rand.Uniform(); y = rand.Uniform();
          if (x*x + y*y < 1)
              IncrementSync (hitCircle);
    }
}
```

```
main () {
    // run N ThreadPi() threads
    // wait to finish
    double pi =
         4*hitCircle/ITER/nThreads;
}
```

Performance

```
SetThreadAffinityMask (GetCurrentThread(),
                       1 << (threadID % nCPUs));
```

- Six-core AMD Phenom II X6, 2.8 GHz
- Two modes of operation
  - No affinity set (threads run on the next available core)
  - Each thread is permanently bound to one of the 6 cores
- Total k threads
- The basic kernel Mutex
  - $\pi \approx 3.13$
  - CPU $\approx$ 16%
  - Requires 2 kernel-mode switches per increment
  - Runs almost twice as slow with 20K threads

```
IncrementSync (LONG *hitCircle) {
    WaitForSingleObject (mutex, INFINITE);
    (*hitCircle) ++;
    ReleaseMutex (mutex);
}
```

k = 60		k = 20K	
No affinity	Affinity	No affinity	Affinity
384K/s	447K/s	278K/s	220K/s

Performance

- AtomicSwap
  - $\pi \approx 3.1405$
  - CPU = 100% (locks up the computer)
  - Unable to start more than 7K threads since the CPU is constantly busy

```
LONG taken = 0;   // shared flag
IncrementSync (LONG *hitCircle) {
    while (InterlockedExchange (&taken, 1)
                                == 1)
        ;
    (*hitCircle) ++;
    taken = 0;
}
```

k = 60		k = 20K	
No affinity	Affinity	No affinity	Affinity
448K/s	485K/s	–	–

- AtomicSwap and yield
  - When cannot obtain mutex, yield to other threads if they are ready to run
  - $\pi \approx 3.1412$
  - CPU = 100%, but computer much more responsive

```
LONG taken = 0;   // shared flag
IncrementSync (LONG *hitCircle) {
    while (InterlockedExchange (&taken, 1)
                                == 1)
        SwitchToThread();
    (*hitCircle) ++;
    taken = 0;
}
```

k = 60		k = 20K	
No affinity	Affinity	No affinity	Affinity
6.8M/s	6.8M/s	12M/s	11.9M/s

Performance

- CRITICAL_SECTION
  - $\pi \approx 3.1417$
  - CPU = 36%
- Interlocked increment
  - $\pi \approx 3.1416$
  - CPU = 100%
  - Fastest method so far
- No sync (naive approach)
  - CPU = 100%
  - Concurrent updates lost due to being held in registers and cache

```
CRITICAL_SECTION cs;
IncrementSync (LONG *hitCircle) {
    EnterCriticalSection (&cs);
    (*hitCircle) ++;
    LeaveCriticalSection(&cs);
}
```

k = 60		k = 20K	
No affinity	Affinity	No affinity	Affinity
6.9M/s	15.9M/s	7.3M/s	12.8M/s

```
IncrementSync (LONG *hitCircle) {
    InterLockedIncrement (hitCircle);
}
```

k = 60		k = 20K	
No affinity	Affinity	No affinity	Affinity
19.4M/s	19.2M/s	19.1M/s	19.0M/s

```
IncrementSync (LONG *hitCircle) {
    (*hitCircle)++;
}
```

k = 60		k = 20K	
No affinity	Affinity	No affinity	Affinity
25.5M/s	19.9M/s	20.6M/s	20.2M/s
$\pi \approx 1.21$	$\pi \approx 1.03$	$\pi \approx 0.96$	$\pi \approx 1.33$

Performance

```
DWORD WINAPI ThreadPi (LONG *hitCircle) {
    LONG counter = 0;
    for (int i=0; i < ITER; i++) {
        // uniform in [0,1]
        x = rand.Uniform(); y = rand.Uniform();
        if (x*x + y*y < 1)
            counter ++;
    }
    InterlockedAdd (hitCircle, counter);
}
```

- No sync (correct approach)
  - $\pi \approx 3.1415$
  - 202M/s, 100% CPU, bottlenecked by rand.Uniform()
- Lessons
  - Kernel mutex is slow, should be avoided
  - CRITICAL_SECTION is the best general mutex
  - Interlocked operations are best for 1-line critical sections
  - Affinity mask makes a big difference in some cases
- If you can write code only using local variables and synchronize rarely, it can be 1000x faster than kernel mutex and 10x faster than Interlocked

Performance

- Example 2: unbounded producer-consumer
- Producer batch = 1
  - Q.size() ≤ 1
- Producer batch = 10
  - Q.size() $\rightarrow \infty$
- PC 1.1
  - Busy spins to enter
  - CPU is high, mostly spent in the kernel
  - Worst method in our comparison

```
int batch;          // PC 1.1
while (true) {
          while (true) {
              WaitForSingleObject(mutex, INFINITE);
              if (Q.size() > 0) {
                    x = Q.pop ();
                    break;
              }
              ReleaseMutex (mutex);
          }
          ReleaseMutex (mutex);
          // now produce
          WaitForSingleObject(mutex, INFINITE);
          for (int i=0; i < batch; i++)
                    Q.add (i+x);
          ReleaseMutex (mutex);
}
```

k = 600		k = 20K	
batch=1	batch=10	batch=1	batch=10
660/sec	187K/sec	**worse**	**worse**

Performance

- PC 1.2 sleeps on semaphore
  - CPU = 20%
- PC 1.4 releases semaphore in bulk
  - Speed-up by 40% over PC 1.2 with batch=10
  - CPU = 20%

```
int batch;          // PC 1.2
while (true) {
        WaitForSingleObject(sema, INFINITE);
        WaitForSingleObject(mutex, INFINITE);
        x = Q.pop ();
        ReleaseMutex (mutex);

        WaitForSingleObject(mutex, INFINITE);
        for (int i=0; i < batch; i++) {
                Q.add (i+x);
                ReleaseSemaphore(sema,1,NULL);
        }
        ReleaseMutex (mutex);
}
```

```
int batch;          // PC 1.4
while (true) {
        WaitForSingleObject(sema, INFINITE);
        WaitForSingleObject(mutex, INFINITE);
        x = Q.pop ();
        ReleaseMutex (mutex);

        WaitForSingleObject(mutex, INFINITE);
        for (int i=0; i < batch; i++)
                Q.add (i+x);
        ReleaseMutex (mutex);
        ReleaseSemaphore(sema,batch,NULL);
}
```

k = 600		k = 20K	
batch=1	batch=10	batch=1	batch=10
275K/s	130K/s	223K/s	112K/s

PC 1.2

k = 600		k = 20K	
batch=1	batch=10	batch=1	batch=10
275K/s	182K/s	223K/s	151K/s

PC 1.4 (hw1)

Performance

- PC 2.1
  - Adds WaitAll
  - CPU = 100%
  - Horrible performance
  - PC 3.2-3.3 similar
- Back to 1.4
  - Over 450% faster than 1.4 for batch=10
  - CPU = 100%

```
HANDLE arr[] = {sema, mutex};     // PC 2.1
while (true) {
          WaitForMultipleObjects(2, arr, true,
                                 INFINITE);
          x = Q.pop ();
          ReleaseMutex (mutex);

          WaitForSingleObject(mutex, INFINITE);
          for (int i=0; i < batch; i++)
                    Q.add (i+x);
          ReleaseMutex (mutex);
          ReleaseSemaphore(sema,batch,NULL);
}
```

```
int batch;          // PC 1.4 with CS
while (true) {
          WaitForSingleObject(sema, INFINITE);
          EnterCriticalSection (&cs);
          x = Q.pop ();
          LeaveCriticalSection (&cs);

          EnterCriticalSection (&cs);
          for (int i=0; i < batch; i++)
                    Q.add (i+x);
          LeaveCriticalSection (&cs);
          ReleaseSemaphore(sema,batch,NULL);
}
```

k = 600		k = 20K	
batch=1	batch=10	batch=1	batch=10
27K/s	**27K/s**	**worse**	**worse**

PC 2.1

k = 600		k = 20K	
batch=1	batch=10	batch=1	batch=10
361K/s	850K/s	280K/s	1.1M/s

PC 1.4 w/CS

Wrap-up

- PC 3.0
  - CPU = 100%
  - Breaks down when Q is persistently small
- PC 3.1
  - Uses kernel events, runs at 450K/s
- PC 3.4
  - CPU = 30%

```
CONDITION_VARIABLE cv;          // PC 3.0
while (true) {
    EnterCriticalSection (&cs);
    while ( Q.size() == 0 )
          SleepConditionVariable (&cv, &cs, ...);
    x = Q.pop ();
    LeaveCriticalSection (&cs);

    EnterCriticalSection (&cs);
    for (int i=0; i < batch; i++)
          Q.add (i+x);
    LeaveCriticalSection (&cs);
    WakeConditionVariable (&cv);
}
```

```
while (true) {      // PC 3.4 (variation)
    EnterCriticalSection (&cs);
    while (Q.size() == 0) {
       LeaveCriticalSection (&cs);
       Sleep (100);   // 100 ms
       EnterCriticalSection (&cs);
    }
    x = Q.pop ();
    LeaveCriticalSection (&cs);

    EnterCriticalSection (&cs);
    for (int i=0; i < batch; i++)
          Q.add (i+x);
    LeaveCriticalSection (&cs);
}
```

k = 600		k = 20K	
batch=1	batch=10	batch=1	batch=10
205K/s	5.9M/s	**78K/s**	7.1M/sec

PC 3.0

k = 600		k = 20K	
batch=1	batch=10	batch=1	batch=10
22M/s	5.9M/s	16.5M/s	7.5M/sec

PC 3.4 (hw2)